Water sources for cyanobacteria below desert rocks in the Negev Desert determined by conductivity

Christopher P. McKay

Space Science Division, NASA Ames Research Center, Moffett Field CA 94035

Chris.McKay@nasa.gov

Abstract

We present year round meteorological and conductivity measurements of colonized hypolithic rocks in the Arava Valley, Negev Desert, Israel. The data indicate that while dew is common in the Negev it is not an important source of moisture for hypolithic organisms at this site. The dominance of cyanobacteria in the hypolithic community are consistent with predictions that cyanobacteria are confined to habitats supplied by rain. To monitor the presence of liquid water under the small Negev rocks we developed and tested a simple field conductivity system based on two wires placed about 0.5 cm apart. Based on 21 replicates recorded for one year in the Negev we conclude that in natural rains (0.25 mm to 6 mm) the variability between sensor readings is between 20 and 60% decreasing with increasing rain amount. We conclude that the simple small electrical conductivity system described here can be used effectively to monitor liquid water levels in lithic habitats. However, the natural variability of these sensors indicates that several replicates should be deployed. The results and method presented have use in arid desert reclamation programs.

In arid deserts and polar regions photosynthetic communities are found below the surface of translucent rocks (Vogel, 1955; Friedmann and Galun, 1974; Cockell and Stokes, 2004; Warren-Rhodes et al., 2006, 2007, 2013; Pointing et al., 2009; Cary et al., 2010; Cowan et al. 2011, Tracy et al., 2010; Wong et al., 2010; Azúa-Bustos et al. 2011; Khan et al., 2011; Chan et al., 2012; Pointing and Belnap, 2012; Stomeo et al., 2013). They are typically found under quartz (Nienow, 2009) but have been reported under flint in the Negev (Friedmann et al., 1967; Berner and Evenari, 1978) under quartz, marble, talc, and two distinct types of carbonate in the Mojave (Smith et al., 2013) and gypsum in the Atacama (Dong et al., 2007). In addition to providing protection against UV (Berner and Evenari, 1978; McKay, 2012, Smith et al., 2013) and physical abrasion is has been assumed that the rock enhances water retention compared to the adjacent soils. In extreme deserts the dominant species found under colonized rocks is the cyanobacteria, *Chroococcidiopsis* (e.g., Warren-Rhodes et al., 2006; Pointing et al., 2009; Cary et al., 2010; Azúa-Bustos et al. 2011; Cowan et al. 2011, Tracy et al., 2010; Chan et al., 2012). *Chroococcidiopsis* is an oxygenic photosynthetic single cell cyanobacteria extremely tolerant to desiccation and radiation (Billi et al., 2000; 2011).

Direct measurements in the laboratory of the spectral properties of hypolithic rocks from the Negev Desert (Berner and Evenari, 1978) and the Mojave Desert (Smith et al. 2013) provide a clear indication of their effect on the light regime. However, the effect of small rocks on water retention is more difficult to assess and requires field measurements. It has been suggested that rain, fog, and dew are all possible moisture sources for hypolithic communities of cyanobacteria but it has proved difficult to isolate these sources and determine their relative contribution in different deserts (McKay et al., 2003; Warren-Rhodes, et al. 2006; 2013; Azúa-Bustos et al., 2011).

Water availability is key to the habitability of the hypolithic environment because the primary producers are cyanobacteria which require water activity levels every close to unity (RH = 100%). Recently, Strong et al. (2013) have shown that hydration is a critical trigger of cyanobacterial photosynthetic activity and that critical hydration thresholds may exist which determine growth. Previous studies have placed lower limits on the water activity of vapor that can support cyanobacteria activity (e.g. Kushner, 1981 (>94%); Potts and Friedmann, 1981 (~98%); Palmer and Friedmann, 1990 (>90%)). It is therefore not surprising that Warren-Rhodes et al. (2006) report that hypolithic cyanobacteria, which are present under translucent rocks in virtually all other deserts, are not present in the arid core region of the Atacama Desert which receives very little rain or fog. Dew has been determined to be ineffective at providing moisture in this area (McKay et al. 2003). Wierzchos et al. (2006, 2011) and Davila et al. (2008) however, have shown that cyanobacteria and associated heterotrophic bacteria can grow inside saline endoevaporitic habitats where moisture is condensed by halite when relative humidity values are above 75%. Thus, liquid water, albeit salty, is generated from nighttime humidity even when there is no rain, dew, or fog.

Here we focus on the water supply to the communities of hypoliths that are found in the Arava Valley in the Negev Desert, which is of particular interest as one of the lowest elevation, hottest, and driest parts of the Negev. It is of interest to determine the seasonal availability and sources of liquid water under the small flint stones that form the desert

pavement in this area (Figure 1). In particular we seek to test the hypothesis that dew can be an important source of water for hypolithic cyanobacteria in the arid regions of the Negev Desert.

Previous studies in the Negev have shown that fog and dew can be frequent and relatively abundant source of liquid water for microbial lithobiontic colonization in this desert (eg. Kidron et al. 2002 and references therein). However, Kidron (1999) has shown that the efficacy of dew and fog as a moisture source decreases sharply with decreasing elevation. Previous studies have tended to focus on sites at higher elevation in the central and western Negev. Previous reports of dew in the Negev are from locations with 90 mm of rain or more and at higher elevation (eg 200m) - more and heaver dew (Kidron 2002). Our site at -145 m is much lower and would be expected therefore to have less effective dew and fog sources. Interestingly, Kidron et al. (2014) point out that cyanobacteria are confined to habitats supplied by rain while lichen can grow if dew is plentiful. As a result, Kidron et al. (2014) suggests that purely cyanobacteria colonization therefore serve as a bioindicator for dewless habitats within the dewy Negev Desert.

In this paper we report on year round measurements of liquid water occurrence beneath colonized rocks in the Arava Valley and correlate this with rain and dew occurrence. We have developed a simple field method for recording conductivity and test it with 21 replicates in this project. The results and method presented have direct use in monitoring the restoration of arid desert environments.

Methods

We describe and test a simple method to detect the presence of liquid water in and under desert rocks and soils based on the large change in electrical conductivity between the wet and dry state. To determine the presence of liquid water we use the conductivity (the inverse of the resistance) between two wires placed under the rock of interest. Conductivity beneath the colonized flint at this site was measured with wires spaced about 0.5 cm apart. The insolated portion of the wires is secured to the rock by epoxy but the bare wires are not and are physically pressed between the rock and soil. They are thus in contact with both the rock and the soil. A schematic of the conductivity circuit and the implementation of the wires on a sample of the Negev flint are shown in Figure 2. As discussed below, the distance between the wires is not critical as the conductivity is not a function of the distance between the measurement points because the resistance is dominated by the contact resistance between the wires and the soil. When a liquid water layer is present under the rock the salts in the soil provide a conducting solution at the two contacts and the resistance drops. The result is that the conductivity increases sharply when liquid water is present beneath the rock.

McKay et al. (2003) used this same approach for multiyear monitoring in the Atacama Desert. Davis et al. (2010) used this method to track the movement and evaporation of artificial rain in the Atacama Desert. Friedmann and McKay (1985) used a modified version of this approach with a filter paper soak in NaCl as a snow detector in the Antarctic (the reference resistance value was a few ohms). Friedmann et al. (1987) used

this same approach to detect wetting events in porous sandstone (the reference resistance values was 2 MΩ).

Initial work on measurement of the bulk moisture content of soils with two electrodes is reviewed in Bunnenberg and Kühn (1980) back to the initial work of Whitney et al. (1897). With two electrodes, contact resistance can be large and variable and this has lead to the development of 4 wire systems for soil resistance measurements (eg. Edlefsen and Anderson 1941) which is now a standard system in use for determination of moisture in soils (eg. White and Zegelin 1995). Typically this involves measurements that integrate soil moisture to depths of a meter or more with the depth set by the spacing between the 4 electrodes.

For the measurement of the thin film of water below a small rock on the desert surface the two wire system is preferable for several reasons. First, the two wire system is smaller and easier to deploy than a 4 wire system. And, secondly, the resistance is determined by the contact resistance and its variation with water content and not the bulk properties of the soil. This is a disadvantage if one is interested in the water content of the soil column below the rock but it is an advantage when the layer of interest is the interface between the rock and the soil below it.

The ideal contact resistance, R_c, between a conductor impressed onto a half space of conductivity, σ, is given by (Hwang et al. 1997). They considered the case of a circular electrode pressed onto an infinite conducting surface. The geometry here is different but the dependence on contact area and soil conductivity is likely to be similar. Hence the Hwang et al. system, which is the only system for which an analytic treatment has been done is used here to illustrate the dependence on contact and bulk resistance. Thus,

$$R_c = (4a\sigma)^{-1} \hspace{4cm} \text{Eq. 1}$$

where a is the radius of the contact area. The resistance of the soil, R_s, between the electrodes is

$$R_c = L(A\sigma)^{-1} \hspace{4cm} \text{Eq. 2}$$

where L is the length and A is the cross-sectional area of the material between the two electrodes. Barker (1989 show that the depth detected is ~L/5 times the spacing between the wires. If the lateral distance detected is similar in both direction then the area is given by $A = 2(L/5)^2$, and Equation 2 becomes

$$R_s = (L\sigma/12.5)^{-1} \hspace{4cm} \text{Eq. 3}$$

Comparing Equations 1 and 3, if a < L/50, as expected, then the contact resistance will dominate and the measured resistance from the two wires will not depend on the spacing between the wires (Hwang et al. 1997) which is confirmed by laboratory tests with moist soils from the Negev site. This mathematical result (Eq. 3) should be considered indicative rather than definitive because of the dependence of Eq. 1 on the geometry of the electrodes and the dependence of Eq. 3 on the assumed depth of the electrical penetration.

Note that Equation 1 is for good electrical contact between the conductor and the resistive half-space. For the wires in our device pressed onto a granular soil the contact is not uniform and the contact resistance will be higher, and somewhat variable, as a result (Hwang et al. 1997).

When a thin film of liquid is present beneath the rock, the presence of salts in the soil result in a conducting solution. This lowers the value of the bulk soil conductivity, σ, and it also creates a better contact between the wires and the soil. The net result is that the measured resistance drops dramatically when the soil is wet (the conductivity goes up). The value obtained when the soil is holding all the water it can – field capacity – represents the maximum conductivity expected in arid soils.

To measure the conductivity we use the circuit shown in Figure 2. The circuit is a half bridge and is the simplest method to determine an unknown resistance by comparison to a known resistance. The value of the reference resister, R, is chosen such to be approximately equal to the value of the resistance between the wires when the system is wet. The results in a value of the output voltage that is about ½ the value of the excitation voltage and ensures that the signal does not saturate while maximizing resolution. Because the value of the resistance between the wires becomes essentially infinite when the soil is dry it is useful to design the circuit such that the ground is attached to the reference resister and hence the input channel, Vx, is always grounded.

For laboratory resistance measurements the excitation voltage used in a half bridge is typically a DC voltage. However this is not suitable for this application because the wet soil is an ionic solution and the repeated application of a DC voltage will polarize the solution. For this reason the excitation voltage should be AC and should be designed to produce the same integer number of positive and negative voltages. The Campbell series of data loggers (CR21, CR10, CR510, and CR1000) have such a command (AC half bridge) built into the data logger. The Campbell CR10 AC half bridge command (P5) returns as output the value of V_x/V, which can then be used to compute the value of resistance R_x shown in Figure 2 given the value of the resister R, that equation is $R_x = R[(V_x/V)^{-1} - 1]$. The conductivity C is then given by $C = 1/R_x$.

We implemented 21 independent conductivity sensors at the site near the Hatzeva Field School in the Arava Valley south of the Dead Sea in the Negev Desert, Israel (Figure 1) at an elevation of 145 m below sea level. The sensors were connected to a CR10 logger via a Campbell AM16/32 multiplex unit. Three conductivity sensors and three relative humidity probes (PCRC-55 RH sensors) were simply buried in the soil by about 1 cm as a comparison to the rocks. Soil temperature was measured with a Campbell 107 probe. Air temperature and relative humidity were measured with a Campbell 207 probe. Dew was recorded with a Campbell leaf wetness sensor placed upward on a surface rock. Rain was measured with a Campbell TE525 with a resolution of 0.25 mm. Photosynthetically active radiation was recorded with a Li-Cor 190 quantum sensor. The system recorded all sensors once each hour and operated for 365 days beginning 31 March 1995 thereby including the wet winter season in this desert (typically January to March).

Results

For our 365 day recording interval the average air temperature was 24.1ºC, the average air relative humidity was 35%, the total rain was 23.6 mm, the average PAR was 191 umole m^{-2} s^{-1}, the maximum hourly average in the summer was 856 umole m^{-2} s^{-1} at noon on 5 June, and the typical hourly average near noon in the winter was 450 umole m^{-2} s^{-1}. Sherman (2010) provides a report of long term rain data from Ein Hatzeva, listing an multi-year average of 29.9 mm, and the value for the winter of 1995-1996 of 20.2 mm. We recorded 20.6 mm from June 1995 to the end of the data set (April 1996).

During a period of no rain and dry conditions, starting on December 26 at 5 pm an artificial uniform watering of all 21 conductivity sensors was conducted in place with a water level larger than any observed rain event during the year. This data is not shown here but has been used to do a comparative study of the 21 sensors. All 21 sensors responded with peak readings near 200 micro-mhos (211±9, n=21). Twelve hours later the readings averaged 76±13 micro-mhos. Twenty four hours later, in the later afternoon, the readings averaged 0.2±0.6 micro-mhos, indicating essentially dry conditions. For several days after this wetting there was a rebound in surface water in the early morning on each day becoming smaller each consecutive day. This is similar to the observations of Davis et al. (2010) for an artificial wetting experiment in the Atacama Desert. Analysis of the response for all 21 conductivity sensors for this wetting experiment shows that there are both systematic and random effects. This is due to subsurface water vapor, condensing on ventral lithic surfaces under conditions where the microclimatic dew point was reached during cold morning conditions. Systematic effects were indicated by some sensors always reading higher than others, while random effect were indicated by some sensors sometimes higher and sometimes lower than other sensors. Overall, about 2/3 of the variance is systematic and 1/3 is random.

All 21 conductivity sensors showed similar peaks throughout the measurement period but with much more variability than observed in the artificial wetting. We have selected one typical sensor to compare to rain and dew as shown in Figure 3. Each rain event, and only rain, causes high conductivity readings. Dew is also shown in Figure 3. High dew values alone do not cause high conductivity readings.

All 21 conductivity sensors responded to individual rain events. A relatively large rain event is seen on 8 Feb at 2 pm - clearly not dew. The rain sensor indicated rain of 3 mm for two consecutive recording intervals for a total rain of 6 mm. In the first interval all 21 conductivity sensor were reading with an average value and standard deviation of 21±5 (n=21) micro-mhos conductivity, in the second interval 89±37 micro-mhos. In another large rain event on 24 March at 4 pm, 6 mm rain was recorded in one 60 min interval. In that interval the conductivity sensor readings indicated 35±20 micro-mhos.

Integrated over the entire year the conductivity sensor can be used to determine the total hours of liquid water conditions under the rocks. Considering all 21 sensors, and taking the indication of water as readings above 2 micro-mhos conductivity, gives an average of 250±180 hours of wetness. By way of comparison the three soil conductivity sensors indicate 390±75 hour of wetness (defined as RH>95%, Warren-Rhodes et al. 2013). The rocks are not wetter than the soil a few cm below the surface.

Smaller rain resulted in larger the variation between the 21 conductivity sensors. This is due to several factors. For the minimum detectable rain (0.25 mm) the number of raindrops on a small rock is a few hundred (250 drops assuming drop diameter of 1 mm and rock area of 10 cm^2) implying an intrinsic variation of sqrt(N)/N of ~ 6%. Additional variation is likely due to variations in the efficiency of water transfer between the rock surface and subsurface which for small rains may be dependent on the rock shape and orientation with respect to wind. Rocks of particular shapes might more effectively conduct thin films of water toward the soil interface. It would be expected that as the rain increased the variability between sensors would decrease. In natural rains the variability was between 20 and 60% while for the calibration wetting it as 5%.

Discussion

We find that while low levels of dew can be measured at the Hatzeva site, dew is not effective at providing moisture to the habitat. This is in agreement with the results of McKay et al. (2003) for the arid core of the Atacama Desert. A caveat to this conclusion is the possibility that a very heavy dew is indistinguishable from a light rain. In our dataset, a very heavy dew may trigger the rain gauge at 0.25 mm and therefore be listed as rain in our analysis. The lack of utility of non-rain sources of moisture in the Arava Valley is in contrast to other locations in the Negev where it has been shown that fog and dew support microbial life (eg. Kidron et al. 2002 and references therein). However, the lower level of dew in the Arava Valley and the dominance of cyanobacteria in the hypolithic community are consistent with predictions (Kidron et al., 2014) that cyanobacteria are confined to habitats supplied by rain. Thus sites in the Negev with cyanobacteria hypolithic communities without epilithic lichen present can indeed serve as a bioindicator for dewless habitats within the dewy Negev Desert. While rain is the only effective source of moisture for the Arava Valley hypolithic communities, it has been shown the non-rain moisture sources can be effective. In particular, Azúa-Bustos et al. (2011) reported hypolith communities supported by coastal fog in the rainless Atacama Desert. Warren-Rhodes et al. (2013) similarly reported hypolith communities supported by coastal fog in the Namib Desert. Of course heavy marine fog is not expected at the inland areas of the Arava Valley. It seems that no example of hypolithic cyanobacteria supported by dew and not rain or coastal fog has been reported.

Based on the comparison of 21 replicates of the conductivity system, we conclude that the simple small electrical conductivity system described here can be used effectively to monitor liquid water levels in lithic habitats. However the natural variability of these sensors indicates that several should be deployed.

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Figure 1. Site image showing the data logger system emplaced near the Hatzeva Field School in the Arava Valley: N30.772, E35.238, -145 m.
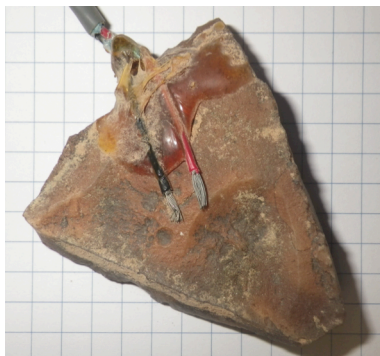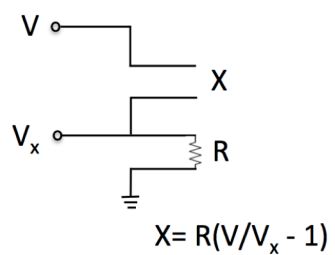
Figure 2. Half bridge circuit to measure resistance of the wires under the rock. X (=R_x) is the unknown resistance between the wires, R is a reference resister (2.2 kΩ) for the Negev application, V is an applied AC voltage and V_x is the measured output. Right image, conductivity sensor on underside of flint rock from Hatzeva in the Negev Desert. Grid squares are 0.5 cm on a side.

Figure 3. Conductivity measured under a colonized Negev rock (upper panel) and rain (middle panel). Rain is specifically associated with high conductivity below the rock. Dew is shown in the lower panel and does not correlate with high conductivity.